Reliability for the 21st Century[1]

Sallie Keller-McNulty
Statistical Sciences Group
Los Alamos National Laboratory
D-1, MS F600
Los Alamos, NM 87544
sallie@lanl.gov

Abstract

The sophistication of science and technology is growing almost exponentially. Government and industry are relying more and more on science's advanced methods to assess reliability coupled with performance, safety, surety, cost, schedule, etc. Unfortunately, policy, cost, schedule, and other constraints imposed by the real world inhibit the ability of researchers to calculate these metrics efficiently and accurately using traditional methods. Because of such constraints, reliability must undergo an evolutionary change. The first step in this evolution is to reinterpret the concepts and responsibilities of scientists responsible for reliability calculations to meet the new century's needs. The next step is to mount a multidisciplinary approach to the quantification of reliability and its associated metrics using both empirical methods and auxiliary data sources, such as expert knowledge, corporate memory, and mathematical modeling and simulation.

1. Introduction

By definition, *Reliability* is the probability a *system* will perform its intended function for at least a given period of time when operated under some specified conditions. The 20th Century solution to this problem[2] has been to define a reliability function as $R(t) = P(T > t) = \int_0^t f(x)dx = 1 - F(t)$, and to use the function as the basis of definition for other important concepts such as failure rate and mean time between failures. Powerful parametric (e.g., Binomial, Poisson, Exponential, Weibull) and nonparametric statistical models have been developed to estimate reliability and its associated properties. These traditional reliability methods were developed for industrial, mass produced products such as electronics and consumer goods. Everything works quite nicely provided we have coherent system representations and clean, typically single, sources of quantitative data about the system.

Problems today are much more complex and include systems such as nuclear weapons, infrastructure networks, super computer codes, jumbo jets, etc. These systems demand more of reliability and the scientists charged with the responsibility of system assessment than our current methodology allows. In many instances it is not possible to mount vast numbers of full system tests, and frequently none are available (Bement et al. 2002). System assessment is complicated by the need to consider more than what has been traditionally considered as reliability because a system's *ability to perform* is intertwined with other concepts such as its age, safety, and surety. In addition, our ability to do reliability assessments may be severely constrained by policy, cost, and schedule, particularly in problems dealing with inherent reliability of an existing system. Therefore we must expand our

[1] Los Alamos National Laboratory Report #LAUR-02-1279
[2] An excellent review of reliability theory and corresponding references can be found in Martz (2002).

definition of the *system* to include all aspects that affect its performance and all constraints (e.g., test schedule) that affect the confidence we have in the assessment. The end result should be a reliability assessment that is an expression of our complete state of knowledge about the system. Statisticians are frequently the scientists responsible for driving the reliability assessment process. Due to the demands stated above, their roles in this process must correspondingly (and significantly) broaden.

2. Motivating Example

As a concrete example of the complexity facing scientists responsible for reliability assessment, consider Science Based Stockpile Stewardship (SBSS) at Los Alamos National Laboratory (LANL) and the history that has brought us to this problem. From its earliest days, LANL has had a prominent role in the development and evaluation of the United States nuclear weapons stockpile, but the end of the Cold War brought significant changes to how this mission could be carried out. There have been significant reductions in the number of weapons, leading to a smaller, "enduring" stockpile. The United States is no longer manufacturing new-design weapons, and it is consolidating facilities across the nuclear weapons complex. In 1992, the United States declared a moratorium on underground nuclear testing; in 1995, the moratorium was extended, and President Clinton decided to pursue a "zero yield" Comprehensive Test Ban Treaty. However, the basic mission of LANL remains unchanged: LANL must evaluate the weapons in the aging nuclear stockpile and certify their safety, reliability, and performance even though the live test data that has traditionally been used for this evaluation can no longer be collected.

To complete this mission, a two-pronged approach of experiments and computational modeling was adopted. The experimental approach is exemplified by the Dual-Axis Radiography for Hydrotesting (DAHRT) facility, which enables experimentors to better understand the nature of explosions. The computational modeling effort is exemplified by the Accelerated Strategic Computing Initiative (ASCI), which uses supercomputers to model the types of complex nuclear experiments that are no longer performed. At a fundamental level, though, the new experimental and computer technologies have not been developed to address science-based stockpile stewardship; rather a "zero yield" policy could be negotiated and implemented because advances in computer technology made it seem feasible that the sophisticated modeling could be done to realize SBSS. In short, the promise of the technology drove the policy. It created an expectation that certain tough questions could be answered with adequate justification.

Alongside the efforts at experimentation and modeling, we (the statistical scientists) have been working to integrate historical data and to quantify the vast resources of expertise at LANL in such a way as to facilitate their inclusion through Bayesian statistical methods. The challenge is to integrate experimental data, computational models, past tests, subsystem tests, and the expert judgment of subject-matter experts to provide a rigorous, quantitative assessment, with associated uncertainties, of the safety, reliability, and performance of the stockpile.

3. The Future

Traditional statistical science approaches to reliability based strictly on the reliability function given in Section 1 are no longer sufficient to address the reliability assessment process for multifaceted 21st Century problems (Keller-McNulty, Wilson, and Wilson 2001). The complexities of big science problems such as SBSS demonstrate the impossibility of static coherent system solutions. Today the overall assessment process is more about "decision-making" than "modeling." Many problems, such as SBSS, are politically and economically charged. Therefore, even the best data collection design and corresponding statistical models for the problem at hand may not be feasible, or even allowed.

Without careful attention to the whole picture, or purpose of the system assessment, the accomplishments of individual scientists can become lost and detached. Figure 1 is a notional representation of several elements of the SBSS problem. Within parts of that representation tradition methodology works well for various questions. For example, event tree methods can be used to define the critical paths for successful completion on the physical experiments and the risks involved that could affect the schedule. But, what happens if an experiment that is needed to help resolve some of the equation-of-state parameterizations for the computational experiments cannot be done? The uncertainty that results must be propagated through the computational models and accounted for in our statements about confidence in our assessments. This in turn will affect the design of other computational experiments. This is not a standard problem addressed through traditional reliability analysis.

The engineering portion of certification depicted in Figure 1 can be thought of as a traditional engineering reliability problem based on coherent system representations. However, there is rarely direct data available on all parts of the system. Therefore, we must develop methodology that can integrate other, related information and be able to propagate information up and down throughout the system representation (Hamada et al. 2002). A major challenge is to then integrate the engineering reliability information with the physics performance assessment, material degration models, etc. In contrast to the discrete nature of the engineering component condition representations of coherent systems, the physics is represented as continuous, time dependent, integrated processes. It is these two elements, engineering and physics, in combination that are needed to understand the condition of the enduring stockpile. Once again our traditional reliability representations and treatments of problems do not address this integrated assessment.

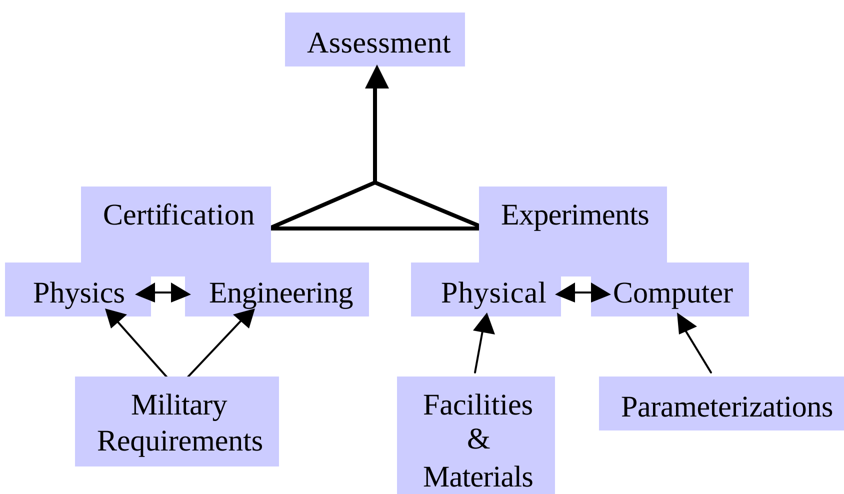

Figure 1. Notional Representation of an Integrated Assessment Process for SBSS.

Our 21st Century reliability challenge is to be able to structure and overlay statistical models on integrated assessment processes, such as that represented in Figure 1. These models will need to be robust enough to support decision-making at various resolutions, (e.g., about a specific experiment, engineering component design, or facility resource allocation to support the overall assessment process). State of knowledge about the system will be a collection of heterogeneous and diverse sources of information. These sources of information will need to be integrated via tractable mathematical models. The information will be coming from very different disciplines, (e.g., physics, materials, chemistry, and engineering). Therefore, uncertainty quantification inherent in the statistical models will need to be flexible to account for natural ways to represent the information (e.g., probability, fuzzy measures, belief functions, possibility theory, etc). With these challenges come wonderful opportunities for the advancement of reliability analysis and the significant advancement of science.

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Reference

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